REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
19-06-2012	Final Report	1-Sep-2008 - 31-Aug-2012

4. TITLE AND SUBTITLE
Single-axis atom-optic accelerometer for Army ground vehicles

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W911NF-08-C-0125

5c. PROGRAM ELEMENT NUMBER
622303

6. AUTHORS
Martin M. Boyd, Adam Black, Todd Gustavson, Thomas Loftus,
Franklin Roller, Thang Tran, Artyom Vitouchkine, Brenton C. Young

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
AOSense, Inc.
767 N Mary Ave

Sunnyvale, CA 94085 -2909

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
55124-PH.4

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The unparalleled accuracies of accelerometers, gyroscopes and gravity sensors based on light-pulse atom interferometry methods hold great promise for a broad range of demanding military and commercial applications in navigation and geophysical exploration. Previous atom optic (AO) sensor development efforts have validated the technology for high-accuracy applications. This program assessed the suitability of the technology for navigation-grade sensors operating on Army platforms. First, we developed a preliminary design for a single-axis

15. SUBJECT TERMS
accelerometer, cold atom, atom interferometer, atom optics, molasses, magneto-optic trap, laser

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Brenton Young
UU	UU	UU	UU		19b. TELEPHONE NUMBER 408-735-9500

Report Title

Single-axis atom-optic accelerometer for Army ground vehicles

ABSTRACT

The unparalleled accuracies of accelerometers, gyroscopes and gravity sensors based on light-pulse atom interferometry methods hold great promise for a broad range of demanding military and commercial applications in navigation and geophysical exploration. Previous atom optic (AO) sensor development efforts have validated the technology for high-accuracy applications. This program assessed the suitability of the technology for navigation-grade sensors operating on Army platforms. First, we developed a preliminary design for a single-axis AO accelerometer for use on an Army all-terrain vehicle (ATV). Various trade studies guided the mechanical, optical, electrical and operational designs of the accelerometer. Sensitivity and error models predicted that the Army accelerometer would meet the specified performance objectives. We experimentally tested innovative technologies that could potentially simplify the accelerometer design. More refined simulations informed the final selection of the techniques for generating cold atoms in sensors operating on moving platforms. Based on the results of the preceding analysis and the technology validation studies, we iterated the accelerometer design and supported a critical design review for the Army accelerometer. Future efforts should build and test the prototype accelerometer.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Adam Black	0.03
Martin Boyd	0.09
Boris Dubetsky	0.01
Todd Gustavson	0.02
Thomas Loftus	0.01
Michael Matthews	0.01
Franklin Roller	0.04
Thang Tran	0.05
Artyom Vitouchkine	0.02
Brenton Young	0.03
FTE Equivalent:	**0.31**
Total Number:	**10**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS

1. Overview

The unparalleled accuracies of accelerometers, gyroscopes and gravity sensors based on light-pulse atom interferometry methods hold great promise for a broad range of demanding military and commercial applications in navigation and geophysical exploration. Laboratory demonstrations of atom optic (AO) accelerometers have achieved 10^{-9} g/Hz$^{1/2}$ noise and $<10^{-9}$ g bias instability, validating the technology for high-accuracy applications.

Performance projections for navigation-grade AO sensors appear extremely favorable, with the long-term prospect for realizing a class of high-performance, compact, robust and low-cost accelerometers for Army applications. A first step toward this goal is the development of a prototype single-axis navigation-grade accelerometer suitable for use on all-terrain vehicles (ATVs) used in Army applications. The size, weight and power (SWAP) constraints of the ATV are largely consistent with demonstrated sensor hardware, allowing us capitalize on existing technology while initially focusing on the specific demands of AO accelerometer operation on a moderately dynamic platform.

Benefits to the Army for this technology broadly include: (1) prospect of developing low-cost, high performance IMUs for integration and coordination of battlespace assets in GPS-denied environments (urban canyons, jamming); (2) advanced attitude determination for weapons systems; and (3) geodetic applications that stem from the exceptional accuracy of the AO accelerometer and thus enable long-term tracking of the gravitational field and its gradient. In contrast with competing technologies, AO sensors provide a common technology base for accelerometer, gyroscope and time-keeping functions, with the prospect of robust, high-accuracy, high-sensitivity, low-cost systems.

This final progress report summarizes our efforts toward developing a prototype Army accelerometer. First it describes the initial sensor models and the various trade studies that factored into a preliminary accelerometer design. Next it summarizes technology validation studies that (1) experimentally investigated potential routes for simplifying the accelerometer and (2) further confirmed through simulations the expected behaviors of innovative features of the Army accelerometer. Finally, it outlines changes to the Army accelerometer as we incorporated new technologies into the sensor design. AOSense hosted a critical design review in June 2011 to present the updated accelerometer design.

2. Summary of Results

To aid in our accelerometer design trade studies, we created a preliminary sensitivity model for a single-axis AO accelerometer. The model first estimates the number of atoms contributing to the interferometer signal for various operational parameters. Next it computes the interferometer signal-to-noise ratio (SNR) based on a combination of theoretical and empirical considerations. Finally, the model estimates the accelerometer sensitivity using the accelerometer SNR and various operational and environmental parameters. Additionally, the trade studies employed a previously developed model that simulates the impact of mechanical platform noise on AO sensor fringes. Inputs to this model included acceleration and rotation data that we collected on a relevant ATV.

Using these analytic tools, we completed a sequence of trade studies that factored into the accelerometer design, including the following: (1) species of cold atom, (2) atom source technology, (3) cold atom production technique, (4) state preparation, (5) atom interferometer methodology, (6) atom detection and (7) system controller architecture. These trade studies yielded a concept design for the accelerometer together with target operational parameters. The accelerometer sensitivity model indicated that the prototype accelerometer should meet the program performance objectives. We developed models for sensor errors and uncertainties due to magnetic field shifts, ac Stark shifts and temperature variations and evaluated these error models for the target operational parameters of the accelerometer.

We developed detailed preliminary functional and physical designs for the accelerometer control, optical and sensor head subsystems. The accelerometer comprises three 19″ rack-mount frames integrated into a shock-mount rack. This sensor packaging is suitable for ATV operation. We compiled detailed lists of the direct materials components of the accelerometer. We identified innovative sensor technologies that would benefit from validation testing prior to the prototype build. Updated projections of the schedule and costs (direct materials, direct labor, ODCs and indirect costs) for fabrication and testing of a prototype accelerometer were consistent with our original cost proposal. A technical report "Army cold atom accelerometer design" dated 31 May 2011 provides detailed descriptions of the preliminary performance and error models, trade studies and the preliminary accelerometer design.

Our preliminary design for the accelerometer laser system had conservatively employed laser technologies that previous sensor devices had empirically validated. AO sensors demand a variety of laser frequencies for laser cooling and trapping, polarization gradient cooling, state preparation, interferometry and detection. Implementing such a versatile laser system can be a driving factor in the sensor volume, power and cost budgets. As a result, simplifications of the laser system could greatly advance AO sensor technology toward our ultimate goal of compact low-cost sensors. Consequently, we experimentally investigated more innovative laser system architectures. We demonstrated a new laser system concept that current and future sensors can adopt to reduce part count, size, power consumption and cost of the laser system.

Our preliminary performance and error models assumed that basic building blocks for cold atom sources, *e.g.* vapor cell loading, 2D-MOTs, 3D-MOTs and optical molasses, would work satisfactorily on the moderate dynamics of an Army ATV platform. These simulations started with a cold atom source with flux comparable to those achievable for laboratory sensors, then modeled the interferometer performance on the ATV platform. Later, we developed new Monte Carlo simulations of laser cooling and trapping to investigate the dynamics of cold atom generation in a reference frame undergoing accelerations and rotations. We ran the simulations using actual motion data collected on an ATV. The numerical results are generally consistent with rough analytical estimates. These simulation results informed the final selection of the cold atom generation techniques for the prototype Army accelerometer. A detailed technical report

"Technology validation for a prototype Army cold atom accelerometer" dated 8 September 2010 documented the results of these experimental and analytical studies.

We iterated the concept designs of the accelerometer sensor head, laser system and control electronics given the inputs from the technology validation studies. A comprehensive survey of techniques for mitigating the effects of platform dynamics guided the selection of the specific physical and operational motion suppression features adopted by the accelerometer. Factoring in the effects of motion suppression, the residual dynamics of the ATV platform drove the selection of the specific laser-cooling techniques employed by the sensor, as well as the time-separation of the atom interferometer laser pulses. The resulting increase in the accelerometer repetition rate relative to our preliminary design trimmed the projected performance margin for the accelerometer sensitivity relative to the original Army specifications. More aggressive atom manipulation techniques may largely compensate for the reduced accelerometer performance margin at higher measurement rates. The improved accelerometer design accommodates dual operational modes: (1) standard interferometry techniques and (2) more aggressive atom manipulation techniques to enhance the acceleration sensitivity. Consequently, the prototype accelerometer can serve as a testbed for comparing operational modes. Once empirical testing of the prototype accelerometer identifies the preferred operational mode, future design iterations can significantly simplify the accelerometer system, thereby improving the SWAP.

Solidification of the revised accelerometer concept design enabled updating to proceed for the detailed functional and physical models for the accelerometer and its subsystems. Analysis of ac Stark and Zeeman shifts of the atomic energy levels guided designs of certain features of the laser system and sensor head. The revised design capitalized on recent advances in AO sensor technologies from parallel research efforts to improve the accelerometer SWAP, cost and risk. The detailed mechanical designs demonstrated that the accelerometer laser system and sensor head will fit into a 5U high 19″ rack-mount frame, while 2U and 3U rack-mount frames will accommodate the control electronics and power supply, respectively. We updated the cost and schedule for building the prototype accelerometer. A technical report "Improved design for Army cold atom accelerometer" dated 31 August 2011 provides detailed documentation on the final accelerometer design.

Contingent on the availability of additional funding, future efforts on this technology development should build and test the prototype accelerometer, then iterate the design to create a production model of the accelerometer. Testing of the accelerometer would validate acceleration sensitivity and stability specifications relative to our analytical model predictions. Performance comparison of the two operational modes would guide the selection of the sensor concept for a production model.